# APPLICATION UNDER UNITED STATES PATENT LAWS

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(M#)

Invention:  **IMIDAZOLIDINE-BASED METAL CARBENE METATHESIS CATALYSTS**

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This is a:

☐ Provisional Application

☒ Regular Utility Application
Of U.S. Provisional Application No.
60/135,493 filed May 24, 1999 and
U.S. Provisional Application No.
60/142,853 filed July 7, 1999

☐ Continuing Application

☐ PCT National Phase Application

☐ Design Application

☐ Reissue Application

☐ Plant Application

☐ Substitute Specification
Sub. Spec Filed _____
        in App. No. ___/_____

☐ Marked up Specification re
Sub. Spec. filed _____
        In App. No ___/_____

# SPECIFICATION

# IMIDAZOLIDINE-BASED METAL CARBENE METATHESIS CATALYSTS

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The present application claims the benefit of U.S. Provisional Application No. 60/135,493, filed May 24, 1999 by inventors Robert H. Grubbs and Matthias Scholl entitled SYNTHESIS OF RUTHENIUM-BASED OLEFIN METATHESIS CATALYSTS COORDINATED WITH 1,-3-DISUBSTITUTED-4,5-DIHYDRO-(4,5-DI-SUBSTITUTED)-IMIDAZOLE-2-YLIDENE LIGANDS [Attorney Docket No. 20072-0254089 (CIT-2993)] and U.S. Provisional Application No. 60/142,853, filed July 7, 1999 by inventors Robert H. Grubbs and Matthias Scholl entitled IMIDAZOLIDINE-BASED METAL CARBENE METATHESIS CATALYSTS [Attorney Docket No. 20072-0254129 (CIT 3021)] which are incorporated herein by reference in their entireties.

## BACKGROUND

Metathesis catalysts have been previously described by for example, United States Patents Nos. 5,312,940, 5,342,909, 5,728,917, 5,750,815, 5,710,298, and 5,831,108 and PCT Publications WO 97/20865 and WO 97/29135 which are all incorporated herein by reference. These publications describe well-defined single component ruthenium or osmium catalysts that possess several advantageous properties. For example, these catalysts are tolerant to a variety of functional groups and generally are more active than previously known metathesis catalysts. In an unexpected and surprising result, the inclusion of an imidazolidine ligand in these metal-carbene complexes has been found to dramatically improve the already advantageous properties of these catalysts. For example, the imidazolidine-based catalysts of the present invention exhibit increased activity and selectivity not only in ring closing metathesis ("RCM") reactions, but also in other metathesis reactions including cross metathesis ("CM") reactions, reactions of acyclic olefins, and ring opening metathesis polymerization ("ROMP") reactions.

## SUMMARY

The present invention relates to novel metathesis catalysts with an imidazolidine-based ligand and to methods for making and using the same. The inventive catalysts are of the
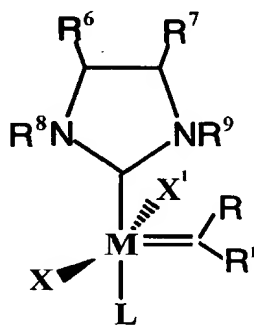
5    formula



wherein:

M is ruthenium or osmium;

X and $X^1$ are each independently an anionic ligand;

10    L is a neutral electron donor ligand; and,

$R$, $R^1$ $R^6$, $R^7$, $R^8$, and $R^9$ are each independently hydrogen or a substituent selected from the group consisting of $C_1$-$C_{20}$ alkyl, $C_2$-$C_{20}$ alkenyl, $C_2$-$C_{20}$ alkynyl, aryl, $C_1$-$C_{20}$ carboxylate, $C_1$-$C_{20}$ alkoxy, $C_2$-$C_{20}$ alkenyloxy, $C_2$-$C_{20}$ alkynyloxy, aryloxy, $C_2$-$C_{20}$ alkoxycarbonyl, $C_1$-$C_{20}$ alkylthiol, aryl thiol, $C_1$-$C_{20}$ alkylsulfonyl and $C_1$-$C_{20}$

15    alkylsulfinyl. Optionally, each of the $R$, $R^1$ $R^6$, $R^7$, $R^8$, and $R^9$ substituent group may be substituted with one or more moieties selected from the group consisting of $C_1$-$C_{10}$ alkyl, $C_1$-$C_{10}$ alkoxy, and aryl which in turn may each be further substituted with one or more groups selected from a halogen, a $C_1$-$C_5$ alkyl, $C_1$-$C_5$ alkoxy, and phenyl. Moreover, any of the catalyst ligands may further include one or more functional groups. Examples of

20    suitable functional groups include but are not limited to: hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen. The inclusion of an imidazolidine ligand to the previously described ruthenium or osmium catalysts has been found to dramatically improve the properties of these complexes. Imidazolidine

25    ligands are also referred to as 4,5-dihydro-imidazole-2-ylidene ligands. Because the imidazolidine-based complexes are extremely active, the amount of catalysts that is required is significantly reduced.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 compares the ROMP activity of COD of representative catalysts of the present

5 invention with previously described metathesis catalysts as determined by $^1$H NMR spectroscopy. The reactions were performed at 20°C with $CD_2Cl_2$ as solvent, a monomer/catalyst ratio of 300, and a catalyst concentration of 0.5 mM.

Figure 2 compares the ROMP activity of COE of representative catalysts of the present

10 invention with previously described metathesis catalysts as determined by $^1$H NMR spectroscopy. The reactions were performed at 20°C with $CD_2Cl_2$ as solvent, a monomer/catalyst ratio of 300, and a catalyst concentration of 0.5 mM.

Figure 3 compares the ROMP activity of COD at an elevated temperature of

15 representative catalysts of the present invention with previously described metathesis catalysts as determined by $^1$H NMR spectroscopy. The reactions were performed at 55°C with $CD_2Cl_2$ as solvent, a monomer/catalyst ratio of 300, and a catalyst concentration of 0.5 mM.

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## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention generally relates to ruthenium and osmium carbene catalysts for use in olefin metathesis reactions. More particularly, the present invention relates to imidazolidine-based ruthenium and osmium carbene catalysts and to methods for making

25 and using the same. The terms "catalyst" and "complex" herein are used interchangeably.

Unmodified ruthenium and osmium carbene complexes have been described in United States Patents Nos. 5,312,940, 5,342,909, 5,728,917, 5,750,815, and 5,710,298, all of which are incorporated herein by reference. The ruthenium and osmium carbene

30 complexes disclosed in these patents all possess metal centers that are formally in the +2 oxidation state, have an electron count of 16, and are penta-coordinated. These catalysts are of the general formula

$$X \underset{X^1}{\overset{L}{\longrightarrow}} M = C \underset{R}{\overset{R^1}{\diagup}}$$
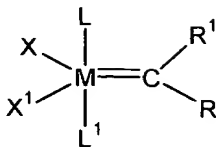
wherein:

M is ruthenium or osmium;

X and $X^1$ are each independently any anionic ligand;

L and $L^1$ are each independently any neutral electron donor ligand;

R and $R^1$ are each independently hydrogen or a substituent selected from the group consisting of $C_1$-$C_{20}$ alkyl, $C_2$-$C_{20}$ alkenyl, $C_2$-$C_{20}$ alkynyl, aryl, $C_1$-$C_{20}$ carboxylate, $C_1$-$C_{20}$ alkoxy, $C_2$-$C_{20}$ alkenyloxy, $C_2$-$C_{20}$ alkynyloxy, aryloxy, $C_2$-$C_{20}$ alkoxycarbonyl, $C_1$-$C_{20}$ alkylthiol, aryl thiol, $C_1$-$C_{20}$ alkylsulfonyl and $C_1$-$C_{20}$ alkylsulfinyl. Optionally, each of the R or $R^1$ substituent group may be substituted with one or more moieties selected from the group consisting of $C_1$-$C_{10}$ alkyl, $C_1$-$C_{10}$ alkoxy, and aryl which in turn may each be further substituted with one or more groups selected from a halogen, a $C_1$-$C_5$ alkyl, $C_1$-$C_5$ alkoxy, and phenyl. Moreover, any of the catalyst ligands may further include one or more functional groups. Examples of suitable functional groups include but are not limited to: hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen.

The catalysts of the present invention are as described above except that $L^1$ is an unsubstituted or substituted imidazolidine,

$$R^8{-}N \underset{\underset{\bullet\bullet}{}}{\overset{R^6 \quad R^7}{\diagdown\diagup}} N{-}R^9$$
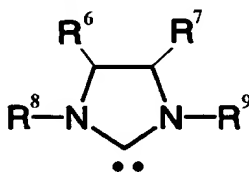
resulting in a complex of the general formula

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$$R^6 \quad R^7$$

$$R^8N \quad NR^9$$

$$\overset{X^1}{\underset{X}{\overset{|}{M}}} = \overset{R}{\underset{R'}{<}}$$

$$L$$
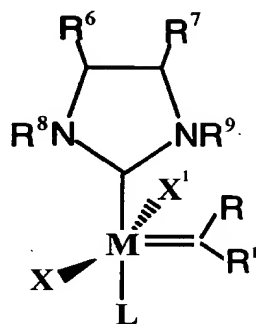
wherein:

$R^6$, $R^7$, $R^8$, and $R^9$ are each independently hydrogen or a substituent selected from the group consisting of $C_1$-$C_{20}$ alkyl, $C_2$-$C_{20}$ alkenyl, $C_2$-$C_{20}$ alkynyl, aryl, $C_1$-$C_{20}$

5    carboxylate, $C_1$-$C_{20}$ alkoxy, $C_2$-$C_{20}$ alkenyloxy, $C_2$-$C_{20}$ alkynyloxy, aryloxy, $C_2$-$C_{20}$ alkoxycarbonyl, $C_1$-$C_{20}$ alkylthiol, aryl thiol, $C_1$-$C_{20}$ alkylsulfonyl and $C_1$-$C_{20}$ alkylsulfinyl. Imidazolidine ligands are also referred to as 4,5-dihydro-imidazole-2-ylidene ligands.

10    In preferred embodiments of the inventive catalysts, the R substituent is hydrogen and the $R^1$ substituent is selected from the group consisting of $C_1$-$C_{20}$ alkyl, $C_2$-$C_{20}$ alkenyl, and aryl. In even more preferred embodiments, the $R^1$ substituent is phenyl or vinyl, optionally substituted with one or more moieties selected from the group consisting of $C_1$-$C_5$ alkyl, $C_1$-$C_5$ alkoxy, phenyl, and a functional group. In especially preferred

15    embodiments, $R^1$ is phenyl or vinyl substituted with one or more moieties selected from the group consisting of chloride, bromide, iodide, fluoride, $-NO_2$, $-NMe_2$, methyl, methoxy and phenyl. In the most preferred embodiments, the $R^1$ substituent is phenyl or -$C=C(CH_3)_2$.

20    In preferred embodiments of the inventive catalysts, L is selected from the group consisting of phosphine, sulfonated phosphine, phosphite, phosphinite, phosphonite, arsine, stibine, ether, amine, amide, imine, sulfoxide, carboxyl, nitrosyl, pyridine, and thioether. In more preferred embodiments, L is a phosphine of the formula $PR^3R^4R^5$, where $R^3$, $R^4$, and $R^5$ are each independently aryl or $C_1$-$C_{10}$ alkyl, particularly primary

25    alkyl, secondary alkyl or cycloalkyl. In the most preferred embodiments, L is each selected from the group consisting of -P(cyclohexyl)$_3$, -P(cyclopentyl)$_3$, -P(isopropyl)$_3$, and -P(phenyl)$_3$.

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In preferred embodiments of the inventive catalysts, X and $X^1$ are each independently hydrogen, halide, or one of the following groups: $C_1$-$C_{20}$ alkyl, aryl, $C_1$-$C_{20}$ alkoxide, aryloxide, $C_3$-$C_{20}$ alkyldiketonate, aryldiketonate, $C_1$-$C_{20}$ carboxylate, arylsulfonate, $C_1$-

5    $C_{20}$ alkylsulfonate, $C_1$-$C_{20}$ alkylthiol, aryl thiol, $C_1$-$C_{20}$ alkylsulfonyl, or $C_1$-$C_{20}$ alkylsulfinyl. Optionally, X and $X^1$ may be substituted with one or more moieties selected from the group consisting of $C_1$-$C_{10}$ alkyl, $C_1$-$C_{10}$ alkoxy, and aryl which in turn may each be further substituted with one or more groups selected from halogen, $C_1$-$C_5$ alkyl, $C_1$-$C_5$ alkoxy, and phenyl. In more preferred embodiments, X and $X^1$ are halide, benzoate, $C_1$-

10    $C_5$ carboxylate, $C_1$-$C_5$ alkyl, phenoxy, $C_1$-$C_5$ alkoxy, $C_1$-$C_5$ alkylthiol, aryl thiol, aryl, and $C_1$-$C_5$ alkyl sulfonate. In even more preferred embodiments, X and $X^1$ are each halide, $CF_3CO_2$, $CH_3CO_2$, $CFH_2CO_2$, $(CH_3)_3CO$, $(CF_3)_2(CH_3)CO$, $(CF_3)(CH_3)_2CO$, PhO, MeO, EtO, tosylate, mesylate, or trifluoromethanesulfonate. In the most preferred embodiments, X and $X^1$ are each chloride.

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In preferred embodiments of the inventive catalysts, $R^6$ and $R^7$ are each independently hydrogen, phenyl, or together form a cycloalkyl or an aryl optionally substituted with one or more moieties selected from the group consisting of $C_1$-$C_{10}$ alkyl, $C_1$-$C_{10}$ alkoxy, aryl, and a functional group selected from the group consisting of hydroxyl, thiol, thioether,

20    ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen; and $R^8$ and $R^9$ are each is independently $C_1$-$C_{10}$ alkyl or aryl optionally substituted with $C_1$-$C_5$ alkyl, $C_1$-$C_5$ alkoxy, aryl, and a functional group selected from the group consisting of hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid,

25    disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen.

In more preferred embodiments, $R^6$ and $R^7$ are both hydrogen or phenyl, or $R^6$ and $R^7$ together form a cycloalkyl group; and $R^8$ and $R^9$ are each either substituted or unsubstituted aryl. Without being bound by theory, it is believed that bulkier $R^8$ and $R^9$

30    groups result in catalysts with improved characteristics such as thermal stability. In especially preferred embodiments, $R^8$ and $R^9$ are the same and each is independently of the formula
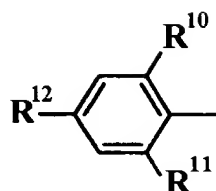
wherein:

$R^{10}$, $R^{11}$, and $R^{12}$ are each independently hydrogen, $C_1$-$C_{10}$ alkyl, $C_1$-$C_{10}$ alkoxy, aryl, or a functional group selected from hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen. In especially preferred embodiments, $R^{10}$, $R^{11}$, and $R^{12}$ are each independently selected from the group consisting of hydrogen, methyl, ethyl, propyl, isopropyl, hydroxyl, and halogen. In the most preferred embodiments, $R^{10}$, $R^{11}$, and $R^{12}$ are the same and are each methyl.
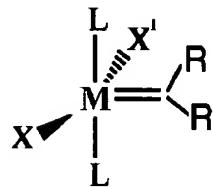
Examples of the most preferred embodiments of the present invention include:
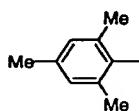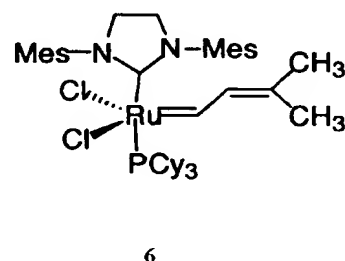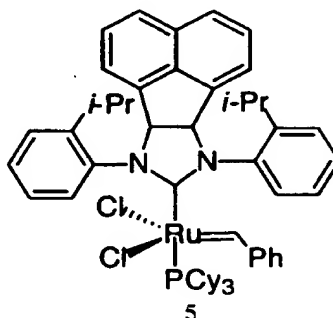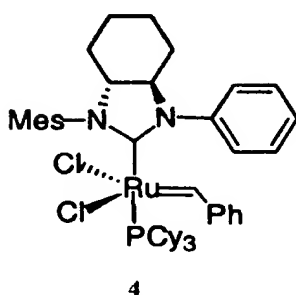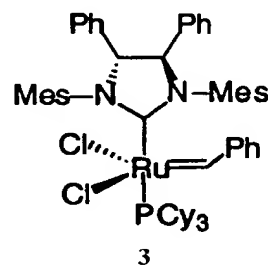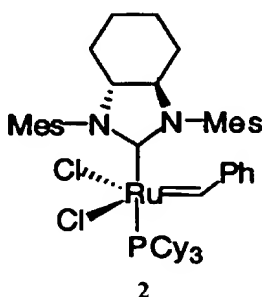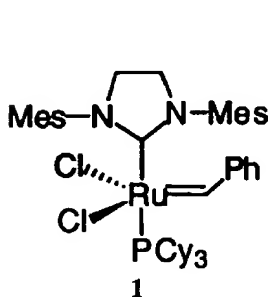


wherein Mes is  (also known as "mesityl"); $i$-Pr is isopropyl; and PCy₃ is
-P(cyclohexyl)₃.

## Synthesis

In general, the catalysts of the present invention are made by contacting an imidazolidine

$$\underset{X}{\overset{L}{\underset{|}{\overset{|}{M}}}}\overset{X^{1}}{\underset{L}{=}}\overset{R}{\underset{R^{1}}{}}$$
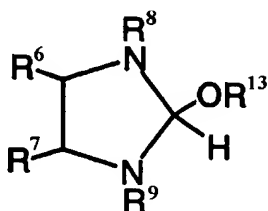
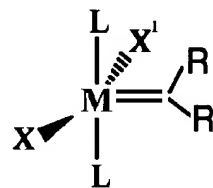with a previously described ruthenium/osmium catalyst                    whereby the

5    imidazolidine replaces one of the L ligands.  The imidazolidine may be made using any suitable method.

In preferred embodiments, the method for making the inventive catalysts comprises contacting an imidazolidine of the general formula

$$\underset{R^{7}}{\overset{R^{6}}{}}\underset{}{\overset{R^{8}}{\underset{N}{}}}\underset{N}{\overset{}{\underset{R^{9}}{}}}\overset{OR^{13}}{\underset{H}{}}$$

with

$$\underset{X}{\overset{L}{\underset{|}{\overset{|}{M}}}}\overset{X^{1}}{\underset{L}{=}}\overset{R}{\underset{R^{1}}{}}$$

10    wherein:

M is ruthenium or osmium;

X and $X^{1}$ are each independently an anionic ligand;

L is a neutral electron donor ligand;

15    R, $R^{1}$ $R^{6}$, $R^{7}$, $R^{8}$, and $R^{9}$ are each independently hydrogen or a substituent selected from the group consisting of $C_{1}$-$C_{20}$ alkyl, $C_{2}$-$C_{20}$ alkenyl, $C_{2}$-$C_{20}$ alkynyl, aryl, $C_{1}$-$C_{20}$ carboxylate, $C_{1}$-$C_{20}$ alkoxy, $C_{2}$-$C_{20}$ alkenyloxy, $C_{2}$-$C_{20}$ alkynyloxy, aryloxy, $C_{2}$-$C_{20}$ alkoxycarbonyl, $C_{1}$-$C_{20}$ alkylthiol, aryl thiol, $C_{1}$-$C_{20}$ alkylsulfonyl and $C_{1}$-$C_{20}$ alkylsulfinyl, the substituent optionally substituted with one or more moieties selected

20    from the group consisting of $C_{1}$-$C_{10}$ alkyl, $C_{1}$-$C_{10}$ alkoxy, aryl, and a functional group selected from the group consisting of hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen; and,

$R^{13}$ is $C_{1}$-$C_{20}$ alkyl or aryl.

If desired, the contacting step may be performed in the presence of heat. Typically, the replacement reaction whereby the imidazolidine displaces one of the L ligands occurs in about 10 minutes in the presence of heat.

5    The imidazolidine may be synthesized by contacting a diamine with a salt to form an imidazolium salt; and then contacting the imidazolium salt with a base (preferably an alkyloxide) to make the imidazolidine in a form suitable for reacting with

$$\begin{array}{c} L \\ | \\ X' \\ X - M = \langle {R \atop R'} \\ | \\ L \end{array}$$
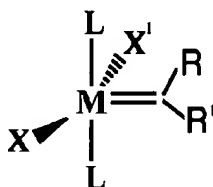
10   One embodiment for the synthetic method is as follows. First, a diketone is contacted with a primary amine ($R-NH_2$ wherein $R^8 = R^9$) or amines ($R^8-NH_2$ and $R^9-NH_2$) to form a diimine which is then reduced to form a diamine.

$$\begin{array}{ccc}
R^6\!\!-\!\!O & & R^6\!\!=\!\!NR^8 \\
& \xrightarrow[\text{Acetone/H}_2\text{O}]{R^8\text{-NH}_2 \atop R^9\text{-NH}_2} & \\
R^7\!\!-\!\!O & & R^7\!\!=\!\!NR^9
\end{array}
\xrightarrow[\text{HCl/MeOH}]{\text{NaCNBH}_3}
\begin{array}{c}
R^6\!\!-\!\!NHR^8 \\
\\
R^7\!\!-\!\!NHR^9
\end{array}$$

In preferred embodiments, $R^8$ and $R^9$ are the same and are each independently $C_1-C_{10}$

15   alkyl or aryl optionally substituted with $C_1-C_5$ alkyl, $C_1-C_5$ alkoxy, aryl, and a functional group selected from the group consisting of hydroxyl, thiol, thioether, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, carbamate, and halogen.

20   When $R^6$ and $R^7$ together form a cycloalkyl and $R^8$ and $R^9$ are the same, the following alternate protocol may be used to make the diamine intermediate of the present invention:
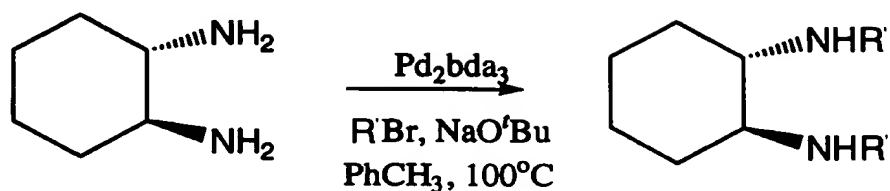
wherein R' represents both $R^8$ and $R^9$ since $R^8 = R^9$. Because a number of optically active primary cycloalkyldiamines are commercially available, this protocol may be used to synthesize optically active imidazolidine ligands. In addition, chiral metathesis

5    complexes are also possible.

The diamine intermediate is used to prepare an imidazolium salt. In one embodiment, ammonium tetrafluoroborate may be used.
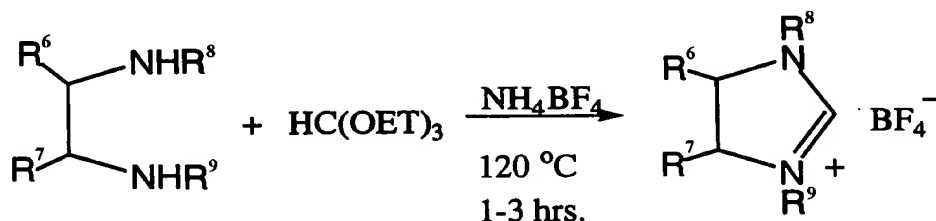


10    The resulting imidazolium salt is then reacted with a base to make the imidazolidine.



Representative examples of suitable bases include the $t$-BuOK/THF and MeONa/MeOH.

15    Metathesis Reactions

    The catalysts of the present invention may be used for any metathesis reaction (*i.e.* ring opening metathesis polymerization, ring closing metathesis, cross metathesis, etc.) by contacting the inventive catalysts with an appropriate olefin. Any olefin may be used and as used herein an olefin is a substituted or unsubstituted alkene and is any compound

20    including cyclic compounds that possess a carbon-carbon double bond. Unlike previously described metathesis catalysts, the inventive complexes can initiate reactions involving even highly substituted olefins such as tri and tetra substituted olefins (*e.g.*,

10

$R^1R^2C=CR^3R^4$ wherein $R^1$, $R^2$, $R^3$, and $R^4$ are independently each a hydrogen or a non-hydrogen moiety) and olefins bearing electron withdrawing groups.

In general, the method for performing a metathesis reaction comprises contacting a
5    suitable olefin with a catalyst of the present invention. To date, the most widely used
catalysts for ROMP and other metathesis reactions are



7           and           8
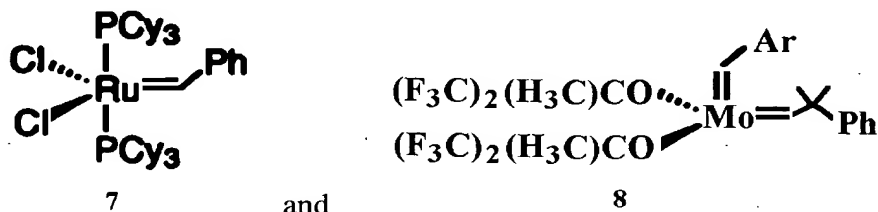
wherein $PCy_3$ is -P(cyclohexyl)$_3$ and Ar is $C_6H_3$-2,6-($^i$PR). The molybdenum catalyst **8**
displays much higher activity than the ruthenium catalyst **7**, thus permitting
10   polymerization of many sterically hindered or electronically deactivated cyclic olefins.
However, the ruthenium catalyst **7** is stable under ambient conditions and tolerates a
much larger range of protic and polar functional groups such as alcohols, acids and
aldehydes. The catalysts of the present invention combine the best features of both
complexes **7** and **8**. In particular, the inventive imidazolidine catalysts rival and often
15   exceed the activity of molybdenum complex **8** while maintaining the stability and
functional group compatibility of ruthenium complex **7**.

The enhanced properties of the inventive catalysts are illustrated by a series of
experiments. For example, Table 1 contains representative results comparing the
20   activities of two representative catalysts (**1** and **2**) of the present invention with complex **7**
in several ring closing metathesis reactions with an acyclic olefin.

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## Table 1: Results of the RCM with 5 mol% cat. in 0.05M CH$_2$Cl$_2$ at reflux

| Entry | Substrate | Product | % Yield (Time, min) with catalyst 7 | % Yield (Time, min) with catalyst 1 | % Yield (Time, min) with catalyst 2[a] |
|-------|-----------|---------|------|------|------|
| 1 | | | 100 (<30) | 100 (5) | 100 (8) |
| 2 | | | 25 (12) 82 (30) | 100 (8) | 100 (12) |
| 3 | | | N.R. (60) | 100 (60) | 65 (20) 92 (12hrs) |
| 4 | | | N.R. (90) | N.R. | 14 (100) 47 (36 hrs) |
| 5 | | | N.R. (90) | 90 (90) | 80 (60) 92 (12 hrs) |
| 6 | | | 39[b] (60) | 35[c] (60) | 55[c] (60) |

E = CO$_2$Et; [a] in CD$_2$Cl$_2$, conversion determined by 1H NMR, [b] E:Z = 1.6:1, [c] E:Z = 2.0:1
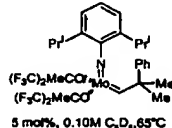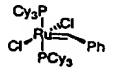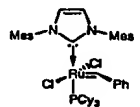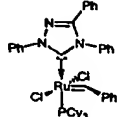
As it can be seen, the ring closure of diethyl diallylmalonate ester (entry 1) is completed in less than 10 minutes at 40 °C with both complexes 1 and 2 while complex 7 requires about 30 minutes. The increased activity of complexes 1 and 2 is most apparent in RCM reactions with more sterically demanding olefins. For example, 2-*tert*-butyl-diethyl diallyl malonate ester (entry 3) can be cyclized with 5 mol% of catalyst 1 in one hour, with 5 mol% of catalyst 2 in twelve hours, while the corresponding reaction with 5 mol% of catalyst 7 does not yield any significant amount of cyclized product. Similarly,

tetrasubstituted olefins (entries 4 and 5) can be prepared in moderate to excellent yields using complexes **1** and **2**.

Table 2 shows the results of the same RCM experiments for previously described
metathesis catalysts including complexes **7** and **8**.

## TABLE 2: RCM ACTIVITY COMPARISONS

| Substrate E = CO₂Et | Product | (F₃C)₂MeCO...Mo... 5 mol%, 0.10M C₆D₆,65°C | Cy₃P Ru 5 mol%, 0.05M CD₂Cl₂,40°C | Mes-N...N-Mes Ru 5 mol%, 0.05M CD₂Cl₂,40°C | Ph triazole Ru 5 mol%, 0.05M CD₂Cl₂,40°C |
|---|---|---|---|---|---|
| | | --- | 30 min 100% | 30 min 100% | 30 min 100% |
| | | 24 hrs 100% | 30 min 82% | 30 min 100% | --- |
| | | 24 hrs 96% | no reaction | 60 min 100% | 30 min 85% |
| | | 24 hrs 96% | no reaction | 90 min 40% | 30 min 53% |
| | | 24 hrs 61% | no reaction | 90 min 95% | 30 min 82% |
| | | --- | 60 min 39% | 60 min 55% | 30 min 73% |
| | | | E:Z=1.6:1 | E:Z=2.0:1 | E:Z=2.3:1 |

Since complexes **1** and **2** are much more reactive than complex **7**, the use of lower catalysts loading for RCM reactions was investigated. The ring closure of diethyl diallylmalonate under the reaction conditions listed in Table 1 was conducted using 0.1, 0.05, and 0.01 mol% of catalysts (**1** or **2**) with respect to the substrate. In the first case, quantitative conversions within one hour were observed with both catalysts; in the second case, the conversion were quantitative with **1** (one hour) and 94% with **2** (three hours). In the third case, the conversions were nearly zero, which indicates that 0.01 mol% is at the lower limit of the catalyst loading for this type of RCM reactions.

The catalysts of the present invention are also useful for ROMP reactions. In general, the method involves contacting the catalyst with a cyclic olefin. The cyclic olefin substrate may be a single cyclic olefin or a combination of cyclic olefins (*i.e.* a mixture of two or more different cyclic olefins). The cyclic olefins may be strained or unstrained,

5      monocyclic or polycyclic, and may optionally include hetero atoms and/or one or more functional groups. Suitable cyclic olefins include but are not limited to norbornene, norbornadiene, dicyclopentadiene, cyclopentene, cycloheptene, cyclooctene, cyclooctadiene, cyclododecene, 7-oxanorbornene, 7-oxanorbornadiene, and derivatives therefrom. Illustrative examples of suitable functional groups include but are not limited

10     to hydroxyl, thiol, ketone, aldehyde, ester, ether, amine, imine, amide, nitro, carboxylic acid, disulfide, carbonate, isocyanate, carbodiimide, carboalkoxy, and halogen. Preferred cyclic olefins include norbornene and dicyclopentadiene and their respective homologs and derivatives. The most preferred cyclic olefin is dicyclopentadiene ("DCPD").

15     The ROMP reaction may occur either in the presence or absence of solvent and may optionally include formulation auxiliaries. Known auxiliaries include antistatics, antioxidants, light stabilizers, plasticizers, dyes, pigments, fillers, reinforcing fibers, lubricants, adhesion promoters, viscosity-increasing agents and demolding enhancers. Illustrative examples of fillers for improving the optical physical, mechanical and

20     electrical properties include glass and quartz in the form of powders, beads and fibers, metal and semi-metal oxides, carbonates (*i.e.* $MgCO_3$, $CaCO_3$), dolomite, metal sulfates (such as gypsum and barite), natural and synthetic silicates (*i.e.* zeolites, wollastonite, feldspars), carbon fibers, and plastics fibers or powders.

25     The inventive catalysts' utility in ROMP reactions was demonstrated with polymerizations both *endo*- and *exo*-DCPD. Exposure of neat DCPD to catalyst **1** (10,000:1) yielded within seconds a hard, highly-crosslinked material. In fact, catalyst loadings as low as 130,000:1 have been used to make high-quality poly-DCPD product. In contrast, previously described ruthenium and osmium catalysts such as **7**, required

30     loadings of 7,000:1 to obtain similar poly-DCPD product.

As demonstrated by the synthesis of telechelic polybutadiene by chain transfer ROMP, the inventive catalysts are also extremely active in the polymerization of unstrained cyclic

olefins. For example, with a catalyst loading of about 12,000:1 (monomer to catalyst **1**),

the yield of telechelic polymers is higher (65%) than that using the bis-phosphine

complex **7** at much lower monomer to catalyst ratio of 2,000:1 (50%).


5      High activities were also observed in the crossmetathesis of acyclic olefins. As an

example, the cross metathesis of 9-decen-1-yl benzoate with *cis*-2-buten-1,4-diol

diacetate catalyzed by **2** gave a high yield (80%) and a higher amount of the *trans* isomer

(E:Z = 9:1) compared to that when the corresponding bis-phosphine complex **7** was used

(E:Z = 4.7:1).

10

## EXAMPLE 1

A synthetic protocol for a representative example of an imidazolidine ligand is as follows.

Other imidazolidine ligands are made analogously.


15     Preparation of 1,2-dimesityl ethylene diimine:

A 300 mL round bottom flask was charged with acetone (50 mL), water (100 mL) and

mesityl amine (10.0 g, 74 mmol). The solution was cooled to 0°C and a solution of 40%

glyoxal in water (5.38 g, 37 mmol) was added slowly. The reaction mixture was allowed

to warm up to room temperature slowly and was stirred for additional 8 hours. The

20     yellow precipitate formed was filtered off, briefly washed with cold acetone and air-dried

to yield 1,2-dimesityl ethylene diimine.


Preparation of 1,2-dimesityl ethylene diamine:

(a) with $H_2$, Pd/C:    A 50 mL round bottom flask was charged with 1,2-dimesityl

25     ethylene diimine (300 mg, 1.01 mmol) and ethanol (20 mL). 10% Pd/C (30 mg) was

added and a hydrogen balloon was attached via a needle. TLC indicated complete spot-

to-spot conversion within 4 hours. The Pd catalyst was filtered off and the volatiles were

pumped off in vacuo to yield 1,2-dimesityl ethylene diamine.

(b) with $NaCNBH_3$:    A 300 mL round bottom flask was charged with 1,2-dimesityl

30     ethylene diimine (3.8 g, 13 mmol), methanol (100 mL) and $NaCNBH_3$ (4,92 g, 78 mmol).

Concentrated HCl was added dropwise to maintain the pH below 4, and the reaction was

stirred at room temperature for 20 hours (overnight). The solution was then diluted with

50 mL water, made basic with NaOH, and extracted thoroughly with $CH_2Cl_2$. The

organic layer war dried over MgSO$_4$, filtered and the solvent was removed in vacuo to yield 1,2-dimesityl ethylene diamine (95% yield).

Preparation of 1,3-dimesityl-4,5-dihydro-imidazolium tetrafluoroborate:

5   A round bottom flask was charged with 1,2-dimesityl ethylene diamine (3.8 g, 12.8 mmol), triethyl orthoformate (15 mL) and ammonium tetrafluoroborate (1.35 g, 12.8 mmol). The reaction mixture was stirred at 120°C for 4 hours at which time TLC indicated complete conversion. Volatiles were removed in vacuo and the product was used as prepared or it could be purified further by recrystallization from ethanol/hexanes.

10

## EXAMPLE 2

Synthesis of Cl$_2$Ru(=CHPh)(PCy$_3$)(1,3-dimesityl-4,5-dihydro-2-imidazole):

The imidazolidine ligand synthesized as detailed in Example 1 is used to prepare the

15   corresponding imidazolidine catalyst ("complex 1")of the present invention. A 100-mL flame dried Schlenk flask equipped with a magnetic stir bar was charged with 1,3-dimesityl-4,5-dihydro-imidazolium tetrafluoroborate (394 mg, 1.0 mmol, 1 equiv.) and dry THF (20 mL) under nitrogen atmosphere. To this suspension, potassium *tert*-butoxide (122 mg, 1.0 mmol, 1 equiv.) was slowly added at room temperature. The

20   tetrafluoroborate salt was dissolved immediately to give a yellow solution. The reaction mixture was allowed to stir at room temperature for one hour, followed by cannula transferring the reaction solution into another 100-mL dry Schlenk flask under Argon. The solvent was evaporated under high vacuum, followed by adding dry benzene (25 mL) and RuCl$_2$(=CHPh)(PCy$_3$)$_2$ (700 mg, 0.85 mmol, 0.85 equiv.). The reaction mixture was

25   heated at 80 °C for 90 minutes. When the reaction was complete indicated by NMR, the volatiles were removed under high vacuum and the residue was washed by dry methanol (20 ml x 4) to give pinkish brown microcrystalline solid (404 mg ) in 56% yield. : $^1$H NMR (CD$_2$Cl$_2$, 400 MHz) δ 19.16 (s, 1H), 7.37-7.05 (m, 9H), 3.88 (s, 4H), 2.56-0.15 (m, 51H); $^{31}$P NMR (CD$_2$Cl$_2$, 161.9 MHz) δ 31.41; HRMS (FAB) C$_{45}$H$_{65}$Cl$_2$N$_2$PRu [M$^+$]

30   848.3306, found 848.3286.

16

## EXAMPLE 3

Synthesis of complex 2

A second example of synthetic protocol for making the inventive catalysts (complex 2)

follows. 1,3-dimesityl-trans-hexahydrobenzoimidazolium tetrafluoroborate (272 mg,

5      0.61 mmol, 1.0 equiv.) was suspended in anhydrous tetrahydrofuran ("THF"; 5 mL) under

inert atmosphere. To this suspension, potassium tert-butoxide ("KO$^t$Bu")was added (65

mg, 0.61 mmol, 1.0 equiv.). Immediately upon addition of KO$^t$Bu, the tetrafluoroborate

salt dissolved completely and the reaction mixture turned yellow. Complex 7,

RuCl$_2$(=CHPh)(PCy$_3$)$_2$ (400 mg, 0.49 mmol), was added to the reaction mixture as a

10     solution in anhydrous benzene (15 mL). The reaction mixture was heated in an oil bath at

80 °C for 80 minutes at which time $^1$H NMR spectrum indicated a ratio of product

(complex 2) to complex 7 of 95:5. Volatiles were removed *in vacuo* and the residue was

washed under inert atmosphere with anhydrous pentane (4X 20 mL) to give pure product

as a pinkish-brown microcrystalline solid (270 mg, 0.3 mmol) in 61% yield. Scheme 1

15     illustrates this protocol for complex 2 as well as for complexes 1 and 3.

## SCHEME 1



20
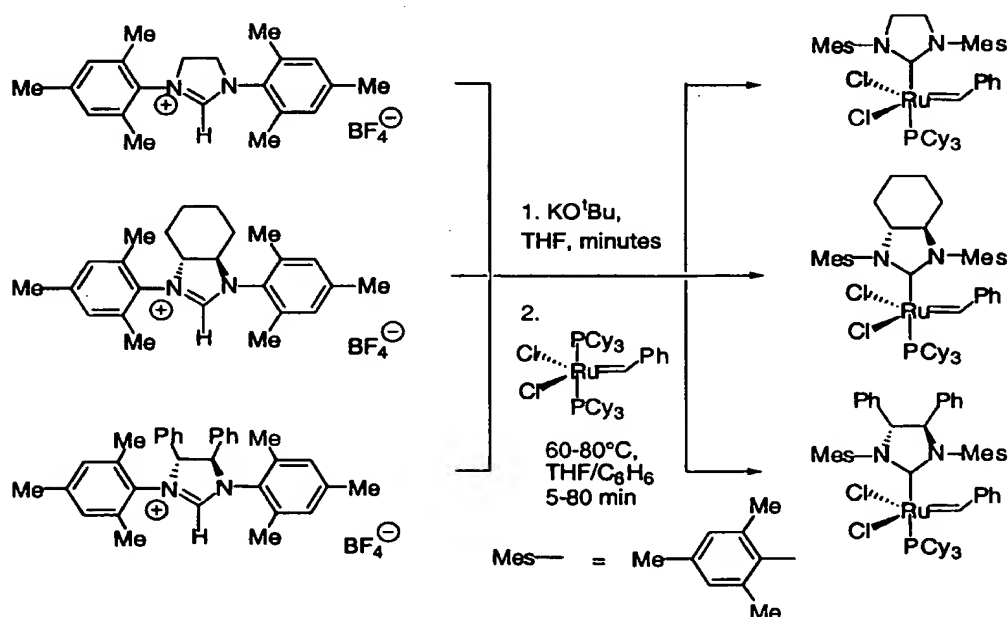
## EXAMPLE 4

The following are representative protocols for several common metathesis reactions.

RCM Reactions

5    Complex 1 (42 mg, 50 μmol, 0.05 equiv.) was added to a solution of diethyl diallylmalonate (240 mg, 1 mmol, 1 equiv.) in methylene chloride (20 mL, 0.05 M). The reaction mixture was refluxed on an oil bath (45 °C) for 5 minutes at which time $^1$H NMR indicated 100% conversion to cyclopent-3-ene-1,1-dicarboxylic acid diethyl ester.

10    Cross Metathesis Reactions:

Complex 2 (11 mg, 12 μmol, 0.023 equiv.) was added to a mixture of 9-decen-1-yl benzoate (145 μL, 0.525 mmol, 1 equiv.) and cis-2-buten-1,4-diol diacetate (160 μL, 1.014 mmol, 1.93 equiv.) in methylene chloride (2.5 mL, 0.21 M). After refluxing for 3.5 hours, the mixture was purified by flash column chromatography to yield the cross

15    metathesis product as a clear, colorless oil (140 mg, 80% yield, E:Z = 9:1).

ROMP Reactions with DCPD:

Complex 1 (6.5 mg, 7.5 μmol, 1 equiv.) in a small amount of $CH_2Cl_2$ (100 μL) was added to a stirring neat dicyclopentadiene (mixture of *exo*- and *endo*-isomers) (10.0 g, 75.6

20    mmol, 10,000 equiv.). Within a few seconds, the reaction mixture became increasingly viscous, warmed up significantly, and solidified shortly thereafter. On cooling, an odor free, nearly colorless solid was obtained.

Telechelic Synthesis:

25    Complex 1 (3.1 mg, 3.7 μmol, 1 equiv.) was added to a stirring mixture of cyclooctadiene (5.00 g, 46.2 mmol, 12,500 equiv.) and 1,4-dichloro-cis-2-butene (1.16 g, 9.28 mmol, 2,500 equiv.). After 8 hours, the reaction mixture was diluted with methylene chloride (1 mL) and poured into an excess of methanol precipitating the dichloro-telechelic polybutadiene as a white solid (4.0 g, 65% yield).

30

Polymerization of 5,6-Dihydroxycyclooctene

In a nitrogen filled drybox, a small vial was charged with 2 mg catalyst (1 equiv.), 150 mg 5,6-dihydroxycyclooctene (1000 equiv.), and 0.25 mL of benzene. The vial was

capped tightly, removed from the drybox, and submerged in a constant temperature oil

bath set at 50 degrees. After 10 hours, a slightly yellow viscous oil formed. Upon the

addition of tetrahydrofuran, a white gel separated and was found to be insoluble in all

common organic solvents. Residual, unreacted monomer could be detected in the

5    tetrahydrofuran layer by $^1$H NMR.

## EXAMPLE 5

To better appreciate the advantageous properties of the inventive catalysts, the ROMP

10    reactions of low strain cyclic olefins, cis, cis-cycloocta-1,5-diene ("COD") and cis-

cyclooctene ("COE") with inventive catalysts 1 and 6
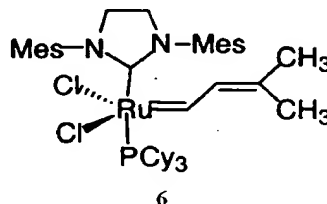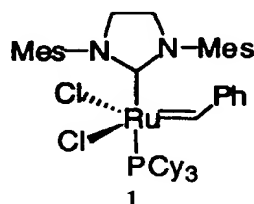


and representative prior art catalysts
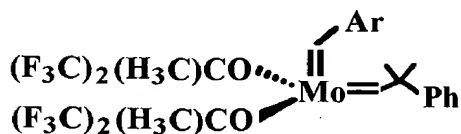


wherein Ar = $C_6H_3$-2,6-($^i$PR) ("catalyst 8")
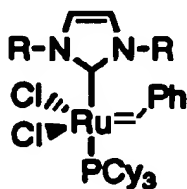


15    and          wherein R = Mes ("catalyst 9") were compared. The molybdenum

catalyst 8 was purchased from Strem Chemicals and recrystallized from pentane at -40 °C

prior to use. For the ROMP kinetics experiments, COD, COE, and $CD_2Cl_2$ were distilled

from $CaH_2$ and bubbled with argon prior to use. All polymerizations were performed

under an atmosphere of nitrogen.

20

The ROMP of COD and COE were catalyzed with the respective catalysts and the percent

monomer converted to polymer was followed over time using $^1$H NMR spectroscopy. As

shown by Figures 1 and 2, the rate of polymerization at 20°C using catalyst 1 was

significantly higher than the molybdenum catalyst **8**. As illustrated by Figure 3, the rate

of polymerization at 55°C using catalysts **6** and **9** were also higher than for the

molybdenum catalyst **8**. Because the propagating species resulting from catalysts **1** and **6**

are the same, the observed difference in polymerization rates between them is believed to

5      be due to the initiation rate. The bulkier benzylidene is believed to facilitate phosphine

dissociation thereby enhancing initiation to a greater extent than the dimenthylvinyl

carbene counterpart. Previous studies have shown that alkylidene electronics have a

relatively small influence on the initiation rate.

10      Although imidazole-based catalysts such as catalyst **9** and the imidazoline-based catalyst

of the present invention may appear structurally similar, they possess vastly different

chemical properties due to the differences in their electronic character of the five

membered ring. For example, the chemical differences between [structure] and

[structure] is as profound as the differences between [structure] and [structure] .
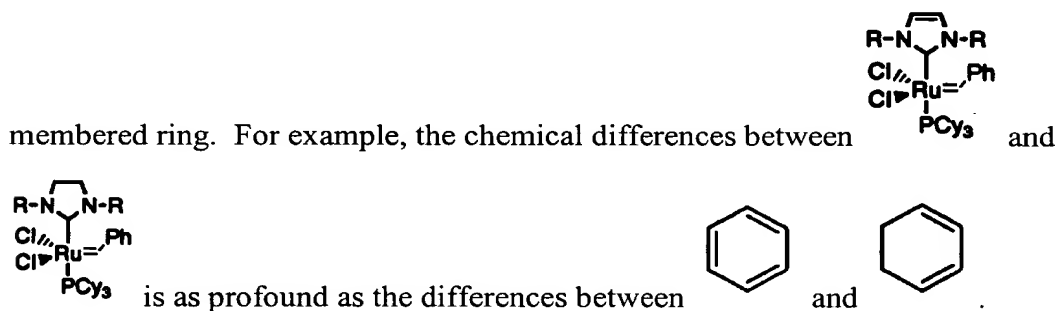
15

## EXAMPLE 6

The catalysts of the present invention are capable of polymerizing a variety of low strain

cyclic olefins including cyclooctadiene, cyclooctene, and several functionalized and

sterically hindered derivatives with extremely low catalyst loadings (up to

5    monomer/catalysts = 100,000). Representative results are shown by Table 3.


**Table 3: ROMP of various low strain cyclic olefins**

| Monomer | Monomer to Catalyst Ratio | Temp. (°C) | Time | Yield (%) | $M_n$ (PDI)[a] | % Trans[b] |
|---------|---------------------------|------------|------|-----------|----------------|-------------|
| 1,5 cyclooctadiene | 100,000 | 55 | 30 min | 85 | 112,400 (2.3) | 70 |
|  | 10,000 | 25 | 24 h | 85 | 92,900 (2.5) | 85 |
|  | 25,000 | 55 | 24 h | 89 | 10,700 (2.1) | 90 |
| cyclooctene | 100,000 | 55 | 5 min | e | e | f |
|  | 10,000 | 25 | 30 min | e | e | f |
|  | 25,000[c] | 55 | 24 h | 75 | 2200 (1.6) | 85 |
| 1-hydroxy 4-cyclooctene | 100,000 | 55 | 5 min | e | e | f |
|  | 10,000 | 25 | 30 min | e | e | f |
|  | 25,000[d] | 55 | 24 h | 85 | 2600 (2.3) | 85 |
| 1-acetoxy-4-cyclooctene | 10,000 | 55 | 5 min | 50 | 103,900 (2.8) | 85 |
|  | 1000 | 25 | 1 h | 60 | 79,300 (3.2) | 90 |
| 5-methylcyclopentene | 1000 | 25 | 24 h | 50 | 23,000 (2.5) | 50 |
| cyclopentene | 1000 | 25 | 24 h | 52 | 9000 (3.5) | 90 |

[a] Determined by $CH_2Cl_2$ or THF GPC and results are reported relative to poly(styrene)
standards; [b] Percent trans olefin in the polymer backbone as determined by 1H and 13C
10   NMR analysis; [c] 1,4-diacetoxy-cis-2-butene was included as a chain transfer agent
("CTA") wherein the Monomer/CTA = 80; [d] Monomer/CTA = 10, [Monomer]$_0$ = 4.5 M
in $C_2H_4Cl_2$; [e] Polymer was insoluble; [f] Not determined.


Elevated temperatures (55 °C) generally increased the yields of polymer while reducing

15   reaction times. The inclusion of acyclic olefins which act as chain transfer agents

controlled the molecular weights. The addition of CTAs is desirable when insoluble

polymers are obtained by ring-opening monomers such as COE in bulk. Polymers

possessing alcohols or acetic ester along their backbone could also be prepared using

functionalized monomers such as 5-hydroxy- or 5-acetoxy-cyclooctene. The functional

20   groups on these polymers could easily be derivatized to form graft copolymers or side-

chain liquid crystalline polymers. In general, $^1$H NMR spectroscopy indicated a

predominantly (70-90%) trans-olefin microstructure in these polymers. As expected for

an equilibrium controlled polymerization where chain transfer occurs, longer

polymerization times resulted in higher trans-olefin values.

5

## EXAMPLE 7

A highly strained monomer, *exo,exo*-5,6-bis(methoxymethyl)-7-oxabicyclo[2.2.1]hept-2-

ene, was polymerized via ROMP reaction using catalyst 1 in the presence of 1,4-

diacetoxy-2-butene as a chain transfer agent. The reaction was conducted in $C_2H_4Cl_2$ at

55 °C for 24 hours and resulted in a bis-(acetoxy) end-terminated polymer in 80% yield

10    (Mn = 6300, PDI 2.0). This result is particularly notable since telechelic polymers

composed of highly strained monomers are relatively difficult to obtain using other

methods. For example, a metathesis degradation approach using a tungsten analog of

catalyst 8 has been used to prepare telechelic poly(oxanorbornene)s and

poly(norbornene)s. However, only certain telechelic polymers are amenable to this

15    approach since the limited ability of the tungsten catalyst to tolerate functional groups

imposes a severe restriction on the range of chain transfer agents that may be used.

Alternatively, a "pulsed addition" approach has been used with catalysts 7 and 8.

However, because monomer and/or CTA must be added in a carefully timed manner, this

approach is relatively difficult to perform and is not readily amenable to industrial

20    applications.

## EXAMPLE 8

1,5-dimethyl-1,5-cyclooctadiene, a sterically hindered, low strain, di-substituted cyclic

25    olefin was polymerized using catalyst 1. The 1,5-dimethyl-1,5-cyclooctadiene used in

this study contained 1,6-dimethyl-1,5-cyclooctadiene (20%) as an inseparable mixture.

This ROMP reaction was performed at 55 °C with monomer/catalyst ratio of 1000 and

resulted in a 90% yield of poly(isoprene) having a $M_n$ of 10,000 and a PDI of 2.3. To the

best of our knowledge, this example represents the first ROMP of this monomer.

30    Subsequent hydrogenation using p-toluenesulfonhydrazide as a hydrogen source afforded

an ethylene-propylene copolymer in quantitative yield (as determined by NMR analysis).

Previously, a six step synthesis was necessary to obtain a similar copolymer via a

metathetical route.

The resulting ethylene-propylene copolymer was not "perfectly" alternating because of the impurity in the 1,5-dimethyl-1-5-cyclooctadiene starting material. However, since trisubstituted alkylidenes were not observed as a side product, poly(isoprene) product

5 having perfectly alternating head to tail microstructure would have likely been formed if a higher grade of 1,5-dimethyl-1-5-cyclooctadiene were used. As a result, practice of the present invention could result in a perfectly alternating ethylene-propylene product.

## EXAMPLE 9

10    2-methyl-1-undecene (110 μL, 0.5 mmol) and 5-hexenyl-1-acetate (170 μL, 1.0 mmol) were simultaneously added *via* syringe to a stirring solution of complex 1 (20 mg, 0.024 mmol, 4.8 mol %) in $CH_2Cl_2$ (2.5 mL). The flask was fitted with a condenser and refluxed under nitrogen for 12 hours. The reaction mixture was then reduced in volume to 0.5 ml and purified directly on a silica gel column (2x10 cm), eluting with 9:1

15    hexane:ethyl acetate. A clear oil was obtained (83 mg, 60% yield, 2.3:1 trans/cis as determined by relative intensity of alkene $^{13}C$ peaks at 125.0 and 124.2 ppm). $^1H$ NMR (300 MHz, $CDCl_3$, ppm): 5.08 (1H, t, $J = 2.0$ Hz), 4.04 (2H, t, $J = 6.0$ Hz), 2.03 (3H, obs s), 2.01-1.91 (2H, m), 1.69-1.59 (2H, m), 1.56 (3H, obs s), 1.47-1.05 (16H, broad m), 1.05-0.84 (3H, t, $J = 6.8$ Hz) $^{13}C$ NMR (75 MHz, $CDCl_3$, ppm): 171.7, 136.7, 136.4,

20    125.0, 124.2, 123.3, 65.1, 40.3, 32.5, 32.3, 30.2, 29.9, 28.8, 28.6, 28.5, 28.0, 26.7, 23.2, 21.5, 16.4, 14.7. $R_f = 0.35$ (9:1 hexane:ethyl acetate); HRMS (EI) calcd for $C_{18}H_{34}O_2$ $[M]^+$ 282.2559, found 282.2556.

## EXAMPLE 10

25

9-Decen-1(*tert*-butyldimethylsilane)-yl (330 μL, 1.0 mmol) and Methyl methacrylate (55 μl, 0.51 mmol) were added simultaneously *via* syringe to a stirring solution of complex 1 (21 mg, 0.026 mmol, 5.2 mol %) in $CH_2Cl_2$ (2.5 ml). The flask was fitted with a condenser and refluxed under nitrogen for 12 hours. The reaction mixture was then

30    reduced in volume to 0.5 ml and purified directly on a silica gel column (2x10 cm), eluting with 9:1 hexane:ethyl acetate. A viscous oil was obtained (110 mg, 62% yield, only *trans* isomer detected in $^1H$ and $^{13}C$ NMR spectra). $^1H$ NMR (300 MHz, $CDCl_3$,

ppm): δ 6.75 (1H, m), 3.71 (3H, s), 3.57 (2H, t, $J$ = 6.3 Hz), 2.14 (2H, m), 1.81 (3H, app

s), 1.50 – 1.05 (12H, broad m), 0.87 (9H, s), 0.02 (6H, s). $^{13}$C NMR (75 MHz, CDCl$_3$,

ppm): δ 169.2, 143.2, 128.0, 63.8, 52.1, 33.4, 30.0, 29.8, 29.2, 29.1, 26.5, 26.3, 18.9.

12.9. $R_f$ = 0.81 (9:1 hexane:ethyl acetate); HRMS (EI) calcd for C$_{19}$H$_{38}$O$_3$Si [M + H]$^+$

5    343.2668, found 343.2677. Elemental analysis calcd: C: 66.61, H: 11.18; found: C:

66.47, H: 11.03.